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Comparative Study of Plume Opacity Measurement Methods

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COMPARATIVE STUDY OF PLUME OPACITY MEASUREMENT METHODS

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ABSTRACT

The opacities of smoke-stack emissions were measured by three methods at thirteen different plants and the results compared. The three opacity measurement methods were trained observer, in-stack transmissometer, and laser radar (lidar). The sources consisted of five coal-fired power plants, four oil-fired power plants, a Portland cement plant, a paper mill kraft recovery furnace, a phosphate fertilizer plant rock dryer, and a small oil-fired boiler at a chemical plant. The instrumental methods of lidar and in-stack transmissometer correlated better with each other than with the observer method and were also more precise than the observer method. The observer measurements were generally lower than the instrumental measurements. This is evidently due to a variable negative bias and/or low sensitivities associated with the observer method when evaluating plumes under viewing conditions where plume visibility is less than desired for the method. The data show that between 10 and 40% opacity (range of opacity emission standards), the observer readings averaged 6 and 11% opacity less than the instrumental readings of lidar and transmissometer respectively, and varied by as much as 25% opacity below to 8% opacity above the instrumental readings.

CONTENTS

Abstract	iii
Figures	vi
Tables	vi
Acknowledgments	vii
1. Introduction	1
2. Opacity Measurement Methods	2
Trained observer	2
In-stack transmissometers	2
Lidar	3
3. Source and Test Descriptions	10
Coal-fired power plants	12
Oil-fired power plants	13
Oil-fired boiler O_c	15
Portland cement plant P	16
Paper mill K	16
Phosphate plant R	16
4. Results	18
Lidar and transmissometer comparison	18
Observer and lidar comparison	18
Observer and transmissometer comparison	22
5. Discussion	23
References	26

FIGURES

<u>Number</u>		<u>Page</u>
1	Mobile lidar system	5
2	Comparison of transmissometer and lidar measured opacities of screen targets	7
3	Plume opacity measurements by lidar versus plume opacity measurements by in-stack transmissometers	19
4	Plume opacity measurements by trained observers versus plume opacity measurements by lidar	20
5	Plume opacity measurements by trained observers versus plume opacity measurements by in-stack transmissometers	21
6	Linear regression relationships between plume opacity measurements by trained observers and in-stack trans- missometer at a coal-fired power plant for different environmental conditions	24

TABLES

<u>Number</u>		<u>Page</u>
1	Mobile Lidar System Characteristics	6
2	Concurrent Opacity Measurements by Different Methods at Various Plants	11

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SECTION 1

INTRODUCTION

Particulate emissions from stationary sources must generally meet opacity as well as mass standards. The opacity standards are established primarily because they are much easier to measure than the mass standards and can be monitored by control agencies and plant operators to determine whether the emission controls required to meet the mass standard are operating properly (1). For this application of dual standards, the opacity standards established by the U. S. Environmental Protection Agency (EPA) are set less stringent than the mass standards so that a violation of the opacity standard will be a clear indication of a decline in the efficiency of the control equipment and a violation of the mass standards (2).

The opacity of an emission is defined in the Federal Register as a measure of the degree to which the emission reduces the transmission of light and obscures the view of an object in the background (3). Consequently, the percent opacity of a plume is determined directly by measuring its percent transmittance and subtracting from 100%. This paper describes a comparative study of three methods of measuring the opacity of smoke-stack plumes: trained observer, in-stack transmissometer, and laser radar (lidar). The comparisons are of concurrently obtained measurements that were made under field conditions at a variety of emission sources.

SECTION 2

OPACITY MEASUREMENT METHODS

TRAINED OBSERVER

The trained observer is the method generally used by control agencies for evaluating the opacity of source emissions, and it is the opacity compliance test method used by EPA (2). The observers are trained at smoke inspector training schools to evaluate opacities of training plumes with prescribed accuracies relative to transmissometer measurement of their opacities. Upon passing the course, they become certified by the school as capable of evaluating the opacities of smoke plumes by visual inspection. When inspecting a plume the method requires that the observer stand (a) at a distance from the plume sufficient to provide a clear view of the emissions, (b) with his line of vision approximately perpendicular to the plume direction, and (c) with the sun oriented in the quadrant to his back. The method also requires that readings be made by observing the plume momentarily at 15 sec intervals over a 6 min period and at the point of greatest opacity. The average of these 24 readings is the observer opacity evaluation of the plume. All of the viewing constraints were used for this study except that the readings were always made on the plume approximately 0.5 stack diameter above the stack exit; also, observer evaluations are not averages of 24 readings. They are usually averages of more than 24 readings taken over periods longer than 6 min which coincided with or overlapped the lidar measurement periods. Four different observers were used during the study.

IN-STACK TRANSMISSOMETERS

In-stack transmissometers are often used to monitor the opacity of stack effluents; their installation is required on some sources by local control agencies and EPA. Design and performance specifications for such

transmissometers have been promulgated by EPA (4). The in-stack opacity data for sampling ports when plant transmissometers were not available. The plant transmissometers were all Lear Siegler* model RM4 instruments. The portable transmissometer was a Lear Siegler model RM41P. All transmissometer opacity data are transmissometer was a Lear Siegler model RM41P. All transmissometer opacity data are for pathlengths equal to the stack exit diameter of the source being measured. When the transmissometer pathlength was different than the stack exit diameter, their opacity measurement was adjusted to represent the opacity of the effluent for a pathlength equal the stack exit diameter as required for monitoring opacity by transmissometer (4).

The RM4 transmissometer was designed and developed in Germany by the Irwin Sick Company to meet the requirements of the German pollution regulatory agency for in-stack particulate monitoring. With modification of the spectral response to meet EPA specifications, the instrument was marketed in the United States by Lear Siegler, Inc. for in-stack opacity monitoring. A detailed description of the RM4 has been published by Beutner (5). The RM4 has subsequently been replaced by a new model RM41 transmissometer.

The RM41P portable transmissometer is basically the RM41 equipped with a probe that is inserted into a standard 10.16 cm (4 inch) stack sampling port for the opacity measurement. The probe is a stainless steel tube with a diameter of 7.6 cm and an overall length of 1.5 m through which light is projected to a small (1.3 cm) retroreflector at the end where it is reflected back to the RM41 transceiver. A slot (1 m by 5.1 cm) in the tube allows the effluent to flow through the beam when inserted into the stack. The reflector and transceiver are protected from the effluent by a clean air purge. For detailed descriptions of the RM41 and RM41P transmissometers, the manufacturer's literature is recommended (6).

LIDAR

The lidar evaluation of plume opacity is made by beaming a short pulse of laser light through the plume and measuring the amount of light back-

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scattered from the pulse by the atmosphere in back of the plume relative to the amount scattered by the atmosphere in front of the plume. This ratio is a measure of the two way transmittance (T^2) of the laser light through the plume. The opacity of the plume is $(1 - T)$. The method was first proposed and demonstrated by the Stanford Research Institute (7). The van mounted lidar used for this study was designed and developed for EPA by the General Electric Company specifically for plume opacity measurements. The lidar is shown in Figure 1. Its design and operational characteristics are shown in Table 1. For a complete description of the lidar system and its operation, the reports on its development are recommended (8,9).

The accuracy of the lidar has been evaluated at various times by making remote measurements on a series of neutral density screen targets of known opacities(9). The screen targets are 1 m in diameter, and their opacities are known from laboratory calibration measurements with conventional transmissometers. The laboratory transmissometers met the EPA design requirements for monitoring opacity (4) and were checked for accuracy with neutral density optical filters. For the remote measurements the targets are usually located approximately 200 m from the lidar. Figure 2 shows a series of measurements made on targets of 24-, 32-, 43-, and 52-% opacity just prior to the study. These measurements and the earlier tests indicate that the accuracy of the lidar is within 3% opacity for opacities under 50%.

Since the lidar uses a ruby (red light) laser and the opacity standards are for green light obscuration, it is necessary to correct the red light lidar measurements to values that would be obtained for green light when the measurements are made on emissions with predominantly submicrometer particle sizes. The correction is not needed if the emissions are composed of particles with mean sizes several micrometers or greater in size; however, for very small submicrometer size particulate emissions, the red light opacity measurement may be as much as 50% lower. No wavelength correction was required for the other methods since the training of the visible emission observer and the spectral response requirements for the in-stack transmissometers are for photopic or green light.

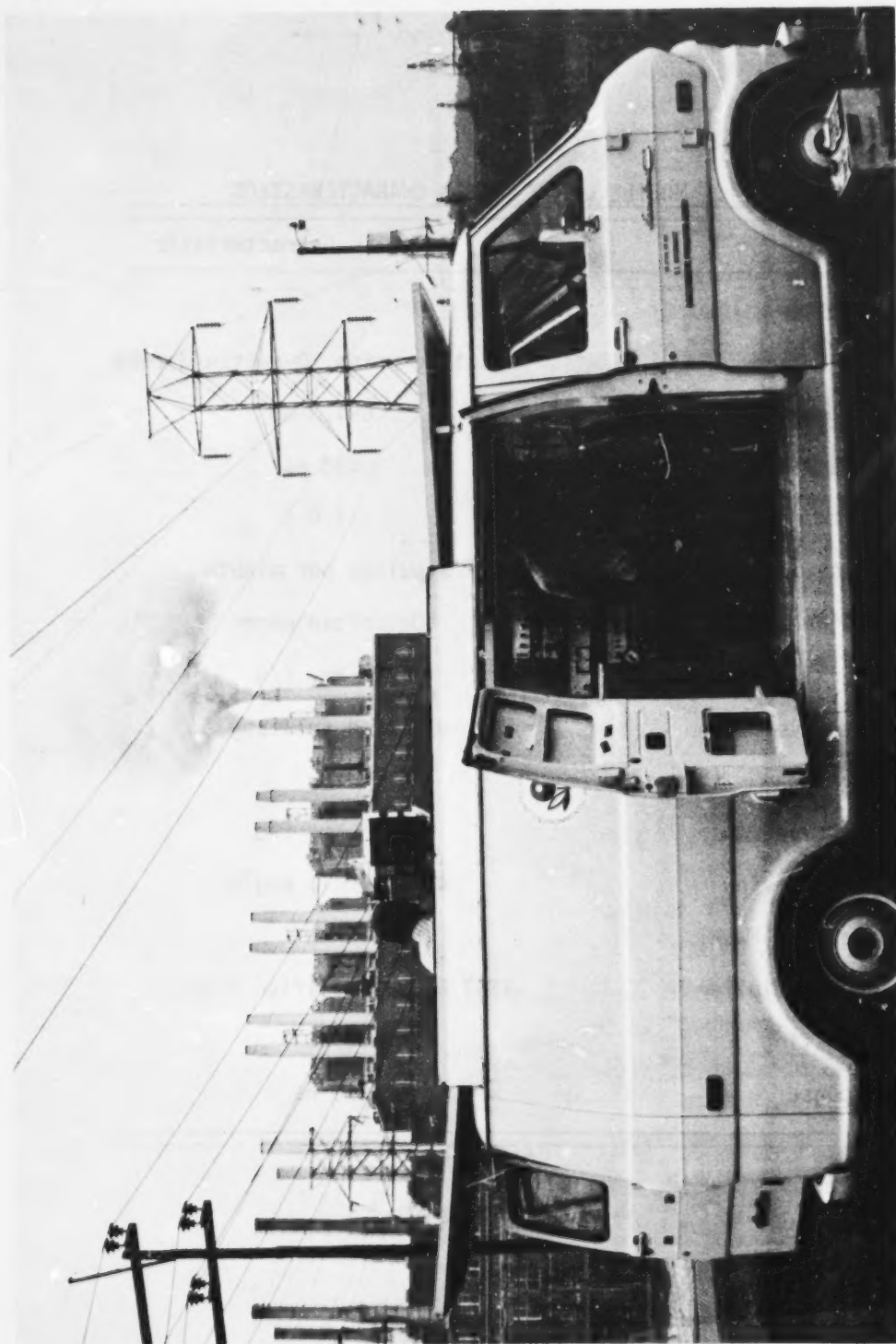


Figure 1. Mobile lidar system.

TABLE 1. MOBILE LIDAR SYSTEM CHARACTERISTICS

Component	Characteristic
Transmitter	
Laser	Rotating prism, Q-switched ruby
Wavelength	694.3 nm
Pulse Width (FWHH)	<30 ns
Maximum Output	1.0 j
Repetition Rate	3 pulses per minute
Cooling	Deionized water
Objective lens	12.7 cm, f/5
Beam Divergence	~0.5 mrad full angle
Receiver	
Objective Lens	15.25 cm, f/b
Field-of-view	4 mrad full angle
Bandpass (FWHH)	1.2 nm
Photomultiplier	IT&T F4084 (modified S-20)
Off-gating	>60 dB
Response	~100 ns

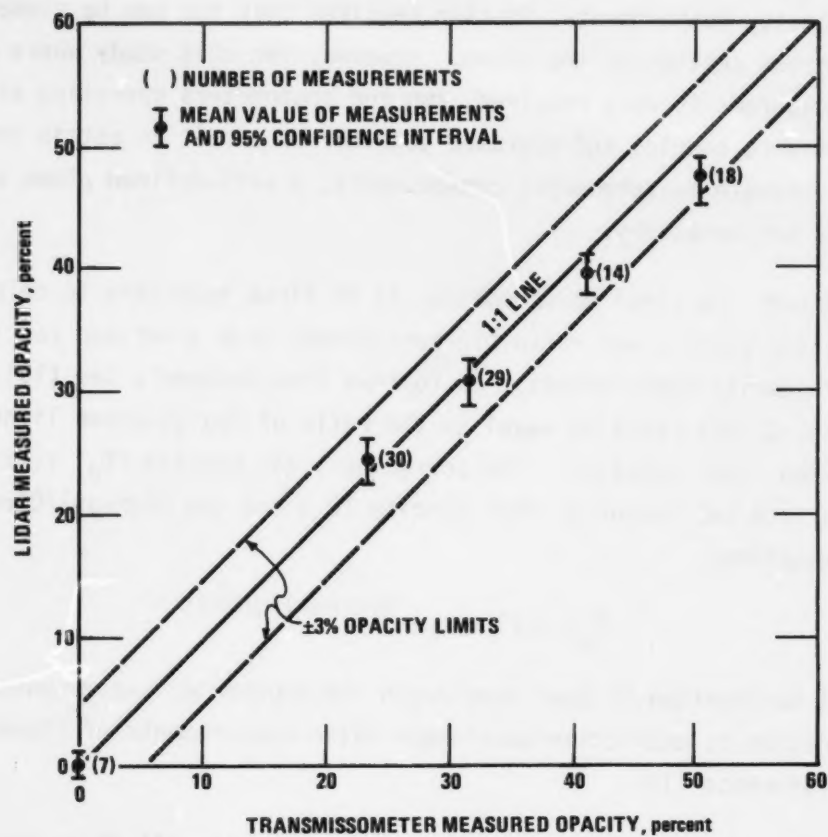


Figure 2. Comparison of transmissometer and lidar measured opacities of screen targets.

The opacity-wavelength characteristics of the submicrometer emissions were measured with dual-wavelength sun photometers. The sun photometer method of determining plume opacity requires measurement of the relative intensity of the sun when viewed beside and through the plume with the photometer. Clearly, this procedure requires that the sun not be obstructed by clouds and that the shadow of the plume be in an accessible location. For accurate opacity measurements, it also requires that the sun be viewed through a defined cross section of the plume. However, for this study where only relative measurements were required, two sun photometers operating at different wavelengths were coupled and operated together as a unit to obtain concurrent opacity-wavelength measurements; consequently, a well-defined plume cross section was not necessary.

To correct the lidar measurements, it is first necessary to calculate the extinction coefficient ratio $Q(\text{green})/Q(\text{red})$ from green and red light sun photometer opacity measurements. It follows from Bouguer's law (10), that the $Q(\text{green})/Q(\text{red})$ ratio is equal to the ratio of $\log(1 - \text{green light opacity})$ to $\log(1 - \text{red light opacity})$. The corrected lidar opacity (O_G) is then calculated from the measured lidar opacity (O_R) and the $Q(\text{green})/Q(\text{red})$ ratio with the equation:

$$O_G = 1 - (1 - O_R)^{Q(\text{green})/Q(\text{red})}.$$

Additional information on dual wavelength sun photometer instrumentation, and its application to extinction-wavelength ratio measurements of plumes can be found in reference (10).

In this study, only the lidar measurements on the oil-fired power plants and boiler emissions required wavelength corrections. Sun photometer measurements were made at all of the oil-fired power plants. The $Q(\text{green})/Q(\text{red})$ ratio of the emissions varied from 1.5 at two of the plants to 2.0 at the other two plants. At the oil-fired boiler, sun photometer measurements were not obtained due to overcast sky conditions and a $Q(\text{green})/Q(\text{red})$ average value estimate of 1.75 from the oil-fired power plant measurements was used to correct the lidar measurements. Sun photometer measurements at the other

SECTION 3

SOURCE AND TEST DESCRIPTIONS

Plume opacity measurements were made at thirteen different plants: five coal-fired power plants, four oil-fired power plants, a portland cement plant, a kraft recovery furnace at a paper mill, a rock dryer at a phosphate fertilizer plant, and a small oil-fired boiler at a chemical plant. The plants were generally located in the Southeastern United States. Plant selection was based primarily on the availability of in-stack monitoring data from plant-owned transmissometers or on the availability of sampling ports for installation of the portable transmissometer to obtain the in-stack opacity data. At seven of the plants, concurrent opacity measurements were obtained with all three methods. Opacity measurements were obtained with the observer method at all plants. However, no opacity measurements were obtained with the in-stack transmissometer method at four of the plants; no opacity measurements were obtained with the lidar method at one of the plants; and no concurrent opacity measurements with the observer and lidar methods were obtained at one of the plants. At four of the coal-fired power plants and at the phosphate plant rock dryer, measurements were made at two different opacity levels. The higher opacity levels were obtained by turning off sections of the electrostatic particulate emission control equipment. Two sets of measurements were made on consecutive days at one of the oil-fired power plants. Table 2 is a list of each concurrent opacity measurement set, the type of plant studied, and the types of opacity measurements made for each measurement set.

TABLE 2. CONCURRENT OPACITY MEASUREMENTS BY DIFFERENT METHODS AT VARIOUS PLANTS

Symbol	Plant Type	Time ^a , m	Lidar N ^b	Opacity ^c , %	Transmissometer Type ^d	Opacity ^e , %	Obs. f	Time ^a , m	Observer N ^b	Opacity ^c , %
C ₁	Coal-fired power plant No. 1	16	10	9±4	--	--	A/B	16/16	14/14	0/0
C ₁	Coal-fired power plant No. 1	12	14	11±5	--	--	A/B	12/12	14/14	0/0
C ₂	Coal-fired power plant No. 2	18	15	53±2	--	--	A/B	18/18	14/14	35±4/33±2 ^h
C ₃	Coal-fired power plant No. 3	11	15	9±2	S	5±1	A/B	11/11	15/15	0/0
C ₃	Coal-fired power plant No. 3	17	25	22±1	S	18±3	A/B	17/17	25/25	0/0
C ₄	Coal-fired power plant No. 4	30	19	28±3	S	36±2	C	15	60	30±2
C ₄	Coal-fired power plant No. 4	20	22	58±3	S	58±7	C	20	84	82±3
C ₅	Coal-fired power plant No. 5	--	--	--	S	13±1	D	30	121	6±0
C ₅	Coal-fired power plant No. 5	--	--	--	S	25±2	D	30/30	121/121	25±1/33±1 ^h
O ₁	Oil-fired power plant No. 1	9	11	23±4	P	19 ^g ±2	D	34	136	27±1
O ₁	Oil-fired power plant No. 1	13	10	31±4	P	20 ^g ±2	D	22	88	30±1
O ₂	Oil-fired power plant No. 2	23	29	10±4	--	--	C	28	110	17±1
O ₃	Oil-fired power plant No. 3	17	16	8±3	P	7±2	C	23	90	7±1
O ₄	Oil-fired power plant No. 4	13	16	10±2	P	3±1	D	21	85	6±1
O _c	Oil-fired boiler (chemical plant)	17	9	11±4	--	--	A	17	10	0
P	Portland cement plant	10	13	10±4	S	14±3	C/D	31/10	124/38	7±1/5±1 ^h
K	Paper mill (kraft recovery furnace)	18	11	5±2	P	4±0	C	22	88	4±1
R	Phosphate plant (rock dryer)	5	6	46±2	P	34±5	--	--	--	--
R	Phosphate plant (rock dryer)	--	--	--	P	28±4	C/D	17/17	68/68	10±1/9±1 ^h
R	Phosphate plant (rock dryer)	--	--	--	P	57±5	C/D	18/16	72/64	32±1/33±2 ^h

^a Test period

^b Number of opacity measurements during test period

^c Mean ± 95% confidence interval of opacity measurements

^d S = Lear Siegler RM4 across-stack transmissometer

P = Lear Siegler RM41P portable transmissometer

^e Mean opacity ± opacity range (estimated by visual inspection of chart)

^f Specific observers are designated A, B, C, and D

^g Transmissometer data not used (see text)

^h Average of the two evaluations used for data analyses

COAL-FIRED POWER PLANTS

The generating capacities of units tested at the five coal-fired power plants ranged from 150 to 680 megawatts. They all burned pulverized coal from southern Appalachia, northwestern Kentucky, or Ohio, and they all had electrostatic particulate emission control equipment.

Coal-fired Power Plant C₁

At this power plant, emissions were measured from two 150-MW units. The emissions from each unit were emitted through separate 61 m high by 3.7 m exit diameter stacks. No in-stack transmissometer data were obtained at the plant. Lidar and observer plume opacity measurements of the emissions were made from a common location 300 and 360 m from the respective plumes. Atmospheric conditions for the lidar measurements were fair. Conditions for the observer measurements were poor. The sky was overcast and the plumes were not visible.

Coal-fired Power Plant C₂

At this power plant, emissions were measured from a 680-MW unit. The emissions were emitted through an 85 m high by 4.6 m exit diameter stack. No in-stack transmissometer data were obtained at the plant. Lidar and observer plume opacity measurements were made from a common location 350 m northeast of the plume. Atmospheric conditions for the lidar measurements were good. Conditions for the observer measurements were poor. The plume background was a bright hazy sky which reduced plume visibility and made the observer measurements difficult.

Coal-fired Power Plant C₃

At this power plant, emissions were measured from a 150-MW unit. The emissions were emitted through a 25 m high by 2.7 m diameter stack on the roof of the plant. A velocity cone at the top of the stack abruptly reduced the stack to an exit diameter of 1.9 m. The top of the stack was 66 m above ground. An LSI RM4 transmissometer was located in the stack approximately 2 m above the plant roof for monitoring opacity. Lidar and observer plume

opacity measurements of emissions were made from a common location 340 m west of the plume. Measurements were made at two emission levels. Atmospheric conditions for the lidar measurements were very good. Conditions for the observer measurements were poor. The plume background was a bright hazy sky which made the plumes not visible to the observer.

Coal-fired Power Plant C₄

At this power plant, emissions were measured from a 154-MW unit. The emissions were emitted through a 91 m high by 4.4 m exit diameter stack. An LSI RM4 was located in the stack at approximately the 46 m level. Lidar and observer plume opacity measurements were made from different positions 300 m north and 200 m southwest of the plume, respectively. Measurements were made at two emission levels. Atmospheric conditions for the lidar measurements were good. Conditions for the observer measurements were fair. The observer was viewing the plume against a partly cloudy background.

Coal-fired Power Plant C₅

At this power plant, emissions were measured from a 300-MW unit. The emissions were emitted through a 178 m high by 4.7 m exit diameter stack. An LSI RM4 transmissometer was located in the stack at the 54 m level. No lidar data were obtained at this plant because the lidar equipment was not available at the time. Observer plume opacity measurements were made from a location 340 m east of the plume. Measurement conditions for the observer were fair. The background varied from partly cloudy blue sky at the low emission level to high scattered clouds and light haze at the high emission level.

OIL-FIRED POWER PLANTS

The generating capacities of the units tested at the four oil-fired power plants ranged from 70 to 520 MW. They all burned residual fuel oil with an additive to inhibit corrosion. None had emission control equipment.

Oil-fired Power Plant O₁

At this power plant, emissions were measured from a large 520-MW capacity boiler burning high sulfur ($\sim 2.5\%$ by weight) residual fuel oil. The emissions were emitted through a 153 m high by 5.2 m exit diameter stack that was breeched with a long horizontal duct (4.3 m wide by 8.4 m high by 51 m long). The LSI RM41P portable transmissometer was installed near the middle of the duct 160 m from the stack exit. Lidar and observer plume opacity measurements were made from a common location 375 m south of the plume. Measurements were made on two consecutive days near noon with the plant operating at normal full load conditions. Atmospheric conditions for the lidar measurements were good both days. Conditions for the observer measurements were fair to good. The sky background varied from hazy with broken clouds the first day to blue with broken clouds the second day.

The in-stack opacity data obtained at this plant clearly did not correlate with the plume opacity measurements and were not used. The measurements showed that the opacity of the plume was much higher than in-stack, indicating that the plume opacity is largely due to an interaction between the effluent and the atmosphere and cannot be monitored by a transmissometer in the stack. This condition was apparently due to the high sulfur content of the fuel oil burned at the plant, which resulted in the condensation and hydration of sulfuric acid. More extensive measurements at this plant made over a range of plant operating conditions support this observation and also show an increase in opacity of the plume with distance from the stack exit (11). The condition was not observed at any of the other plants. The lidar and observer plume opacity measurement data are used for this correlation study since they were made on the plume at the same point.

Oil-fired Power Plant O₂

At this power plant, emissions were measured from a 380-MW unit that was burning a mixture of 20% gas and 80% medium sulfur ($\sim 1.5\%$ by weight) residual fuel oil. The emissions were emitted through a 106 m high by 4.6 m exit diameter stack. No in-stack transmissometer opacity data were obtained at this plant. Lidar and observer plume opacity measurements were made from a

common location 315 m southwest of the plume. Atmospheric conditions for the lidar measurements were good. Conditions for the observer measurements were good. The plume was viewed against a clear blue sky.

Oil-fired Power Plant O₃

At this power plant, emissions were measured from a small 70-MW unit that was burning a medium sulfur ($\sim 1.5\%$ by weight) residual fuel oil. The emissions were emitted to the atmosphere through a 45.6 m high by 3.3 m exit diameter stack. The in-stack opacity was measured with the LSI RM41P portable transmissometer that was installed in the stack 3 m from the stack exit. Lidar plume opacity measurements were made from a location 320 m east of the plume and observer plume opacity measurements were made from a location 152 m southwest of the plume. Atmospheric conditions for the lidar measurements were fair. Conditions for the observer measurements were good. The observer evaluation of the plume was made against a blue sky background.

Oil-fired Power Plant O₄

At this power plant, emissions were measured from a 190-MW unit burning a medium sulfur ($\sim 1.1\%$ by weight) residual fuel oil. The emissions were emitted through a 60 m high by 3 m exit diameter stack. The in-stack opacity was measured with the LSI RM41P portable transmissometer, that was installed in the stack approximately 30 m from the stack exit. Lidar and observer plume opacity measurements were made from a common location 260 m southwest of the plume. Atmospheric conditions for the lidar measurements were poor. Conditions for the observer measurements were good. Observer evaluations were made against a blue sky background.

OIL-FIRED BOILER O_c

This source was a small oil-fired industrial boiler at a chemical plant. The emissions were emitted through a 53 m high by 3.7 m exit diameter stack. No in-stack transmissometer data were obtained at the plant. Lidar and observer measurements were made from a common location 280 m from the plume.

Atmospheric conditions for the lidar measurements were fair. Conditions for the observer measurements were poor. The plume was viewed against an overcast sky, and was not visible except for occasional puffs that were not measured.

PORTLAND CEMENT PLANT P

At this source, emissions were measured from a wet process rotary cement kiln. The emissions were emitted through a 76 m high by 4.6 m exit diameter stack. Particulate emissions were controlled with electrostatic precipitators. The LSI RM41P portable transmissometer was installed in the stack breeching 15 m from the bottom of the stack for in-stack opacity measurement. Lidar and observer plume opacity measurements were made from different positions 240 m southeast of the plume and 150 m west of the plume, respectively. Atmospheric conditions for the lidar measurements were good. Conditions for the observer measurements were good. Conditions for the observer measurements were fair. The observer evaluations were made while viewing the plume against a clear blue sky; however, the data were taken late in the day near sunset, which may have made the plume difficult to read.

PAPER MILL K

At this source, emissions were measured from the kraft recovery furnace at a paper mill. The emissions were emitted through a 93 m high by 2.8 m exit diameter stack. Particulate emissions were controlled with electrostatic precipitators. An LSI RM4 transmissometer was located in the stack approximately 5 m from the stack exit. Lidar and observer plume opacity measurements were made from a common location 700 m southeast of the plume. Conditions for the lidar and observer measurements were good. Observer evaluation of the plume was made against a clear blue sky background.

PHOSPHATE PLANT R

At this source, emissions were measured from a phosphate fertilizer plant (rock dryer). The emissions were emitted through a 25 m high by 2 m exit diameter stack. Particulate emissions were controlled with

electrostatic precipitators. The LSI RM41P portable transmissometer was installed in the stack approximately 2 m from the stack exit for in-stack opacity measurements. Lidar and observer plume opacity measurements were made from different positions 246 m southeast and 120 m west of the plume, respectively. Atmospheric conditions for the lidar measurements went from fair to impossible. After obtaining one series of lidar measurements, a conveyor upwind of the stack was put into operation and interference from particulate emissions from the conveyor contaminated the atmosphere around the stack and made its scatter too irregular and variable to obtain additional lidar measurements. The observer plume opacity measurements were not made concurrent with the lidar measurements but were made at two emission levels. Conditions for the observer measurements were good. The plume was evaluated against a clear blue sky.

SECTION 4

RESULTS

The comparisons between the three opacity measurement methods are shown in Figures 3, 4, and 5. The correlation coefficients, linear regression lines and their 95% confidence intervals are calculated and shown in the figures. The comparisons are of concurrently obtained measurements on relatively steady state emissions. Whenever the opacity of a plume was evaluated by more than one observer during a test, the evaluations were averaged to give a single data point. To prevent measurements from one plant overly affecting a comparison, no more than two emission levels were studied or two data points generated from any one plant. In analyzing the data, the results for opacities between 10 and 40% are considered most important because they form the range of the opacity emission standards.

LIDAR AND TRANSMISSOMETER COMPARISON

The best correlation observed was between the lidar and in-stack transmissometer opacity measurement methods (Figure 3). The coefficient of correlation between the methods was 0.95, and the linear regression line was within 3% opacity of the ideal one-to-one relationship over the entire range of opacities studied. Over the 10 to 40% opacity range, the measurement differences between the methods (lidar-transmissometer) ranged from -8 to +12% opacity, and the lidar measurements averaged 2.2% opacity higher than the in-stack transmissometer measurements.

OBSERVER AND LIDAR COMPARISON

The next best correlation was observed between the observer and lidar opacity measurement methods (Figure 4). The coefficient of correlation between the methods was 0.88. The linear regression line was within $\pm 5\%$ opacity of the ideal one-to-one relationship over the entire range of

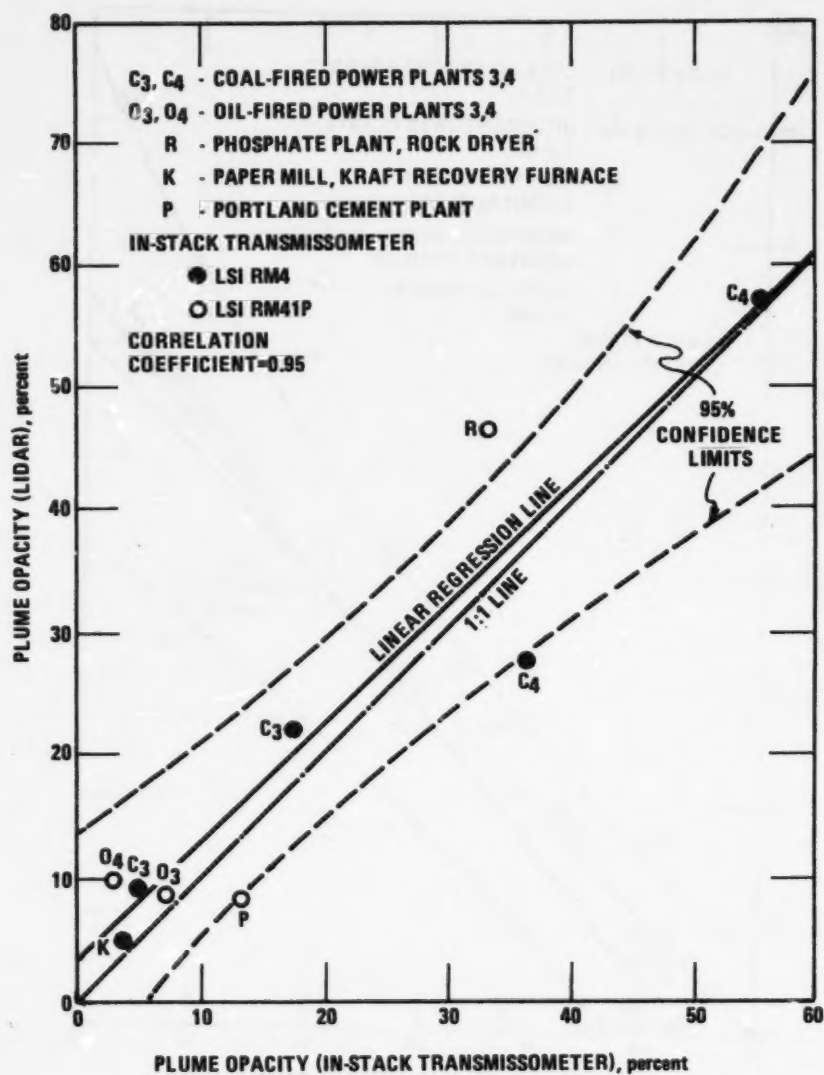


Figure 3. Plume opacity measurements by lidar versus plume opacity measurements by in-stack transmissometers.

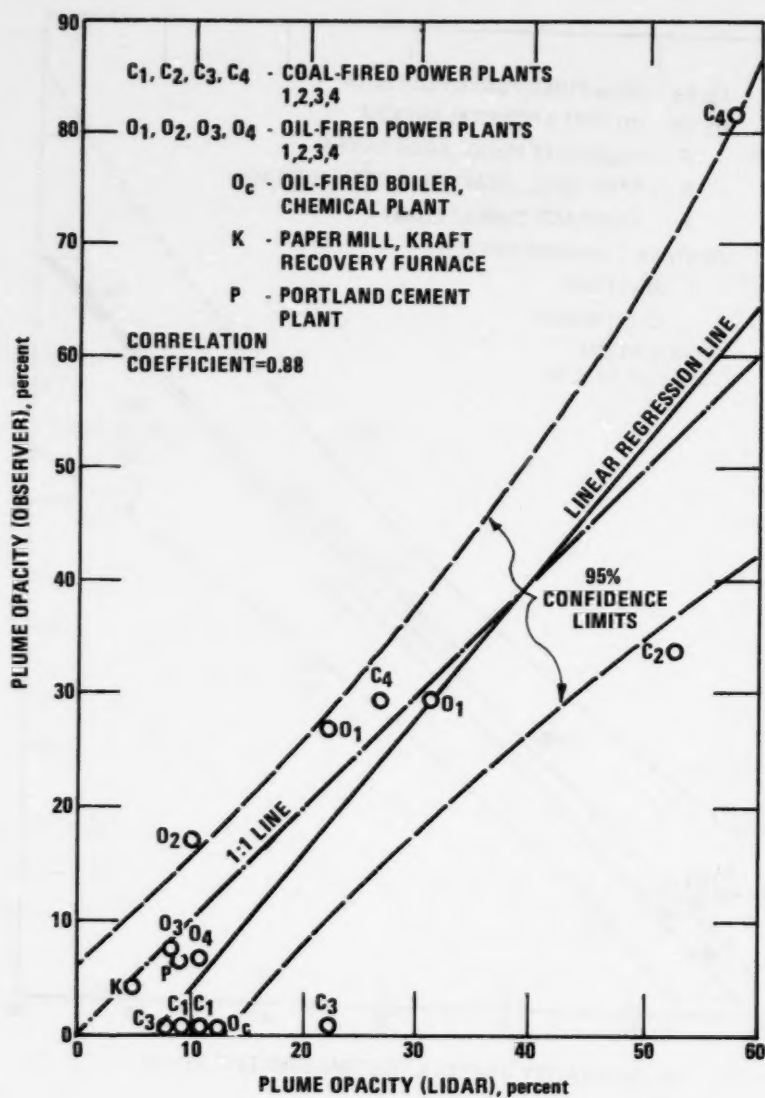


Figure 4. Plume opacity measurements by trained observers versus plume opacity measurements by lidar.

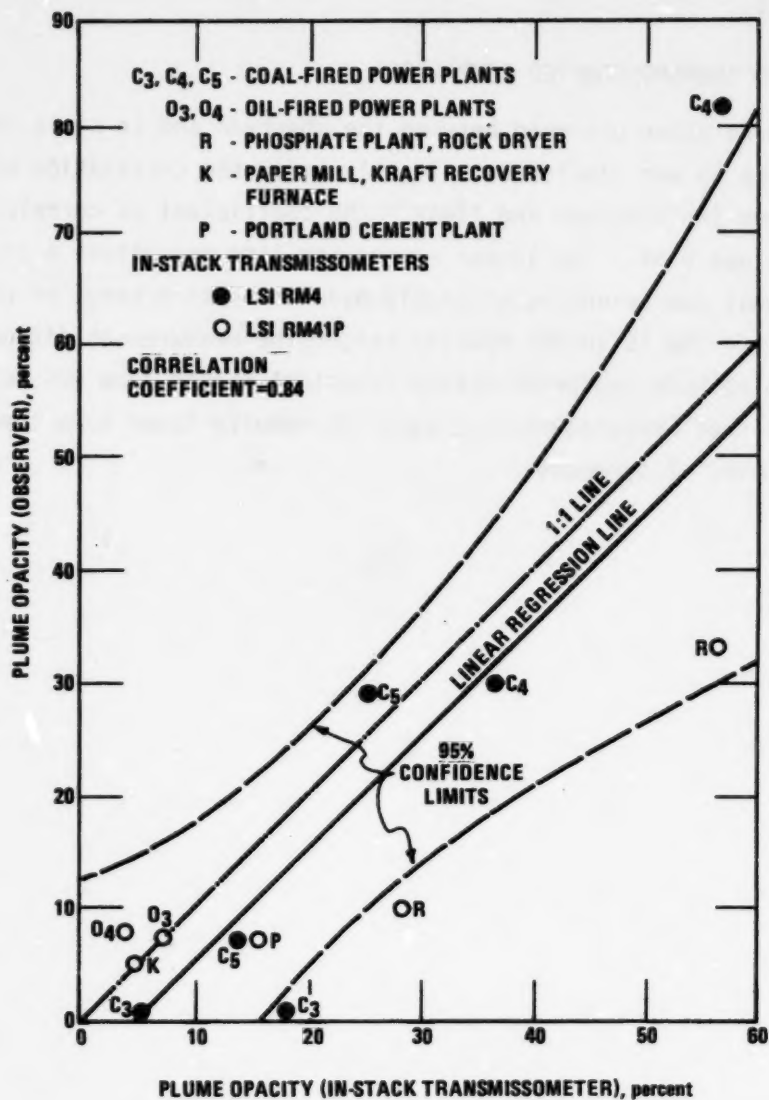


Figure 5. Plume opacity measurements by trained observers versus plume opacity measurements by in-stack transmissometers.

opacities studied. Over the 10 to 40% opacity range, the measurement differences between the methods (observer-lidar) ranged from -22 to 7% opacity, and the observer measurements averaged 5.9% opacity lower than the lidar measurements.

OBSERVER AND TRANSMISSOMETER COMPARISON

The correlation observed between the observer and in-stack transmissometer (Figure 5) was similar but slightly below the correlation observed above between the observer and lidar. The coefficient of correlation between the methods was 0.84. The linear regression line was offset 4 to 6% opacity from the ideal one-to-one relationship over the entire range of opacities studied. Over the 10 to 40% opacity range, the measurement differences between the methods (observer-transmissometer) ranged from -24 to +4% opacity, and the observer measurements averaged 11% opacity lower than the in-stack transmissometer measurements.

SECTION 5

DISCUSSION

The results of the study show that of the three opacity measurement methods studied (lidar, observer, and in-stack transmissometer), the instrumental methods of lidar and in-stack transmissometer correlated best (correlation coefficient 0.95). The observer and lidar correlation was second (correlation coefficient 0.88), and the observer and in-stack transmissometer correlation was worst (correlation coefficient 0.84). The data also show that the observer opacity measurements were generally lower than either the lidar or the in-stack transmissometer opacity measurements.

The lower opacity measurements by the observer method and its relatively poor correlation with instrumental methods is to be expected whenever the comparison is of data obtained under a variety of environmental lighting and plume background viewing conditions. It is primarily due to the low measurements associated with the observer method when evaluating plumes under less than desirable viewing conditions. Low observer opacity measurements relative to transmissometer opacity measurements has also been observed by Hamil (12) during a series of comparative tests between observers and in-stack transmissometers that were conducted at a coal-fired power plant under different environmental conditions. Their data (Figure 6) show that the low observer measurements were related to the environmental lighting and background viewing conditions of the plumes which caused a reduction in sensitivity and/or negative bias of the observer method. In Figure 6, a reduction in sensitivity and/or negative bias of the observer method relative to the transmissometer are represented by low slopes (less than 1) and/or negative translations of the curves, respectively. Low observer opacity measurements were also reported by Hood (13) for a comparative study between the observer and in-stack transmissometer opacity measurement methods at a kraft recovery furnace.

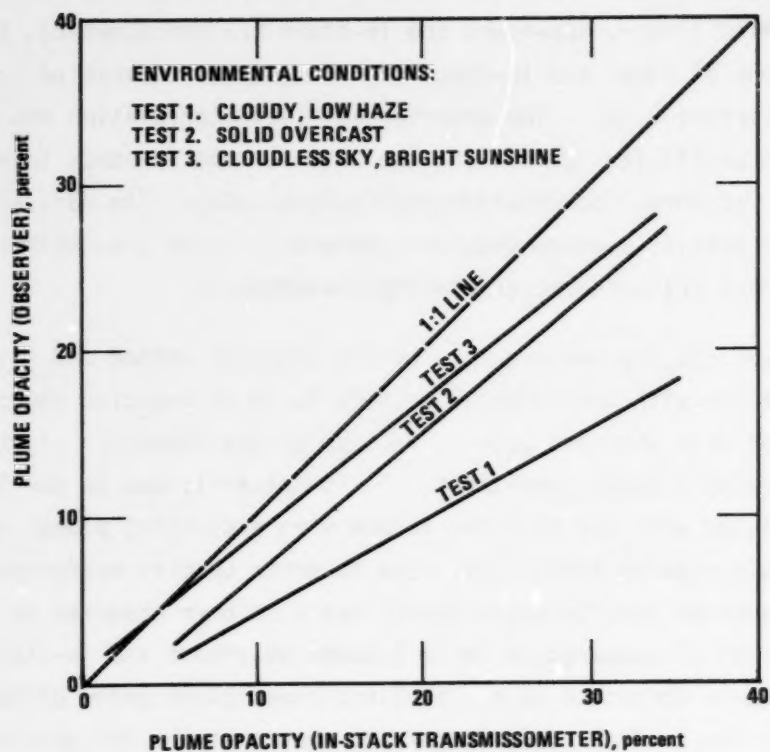


Figure 6. Linear regression relationships between plume opacity measurements by trained observers and in-stack transmissometer at a coal-fired power plant for different environmental conditions(12).

A variable negative bias of the observer opacity measurement method is recognized by EPA, and its significance with respect to the enforcement of opacity standards by the trained observer (Compliance Test Method 9) is discussed in the introduction to the method (2). From the enforcement point of view, it is important to note that over the important 10 to 40% opacity range of the opacity emission standards, the data show that no observer measurements were greater than in-stack transmissometer or lidar measurements by more than 8% opacity.

Although the data reported here have been analyzed statistically to show the degree of correlation and linear regression line relationships observed between the three measurement methods, the results are based on too little data to show much more than trends. More data are needed to completely evaluate the methods. It is likely that with more data on the general application of the methods, (a) the degree of correlation and relative accuracy indicated for the instrumental methods of lidar and in-stack transmissometer will not change significantly, (b) the correlations between the observer and the instrumental methods will become similar but remain below the correlation observed between the instrumental methods, and (c) the observer measurements will continue to be generally lower than the instrumental measurements. However, comparisons of the methods at specific sources at specific times may show better or worse correlations and accuracies. These differences will be related to the specific atmospheric conditions and/or real in-stack and plume opacity differences.

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